

INVITED PAPER

T2SL Digital Focal Plane Arrays for Earth Remote Sensing Applications

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ABSTRACT

Long-wavelength infrared (LWIR) focal plane arrays (FPAs) needed for Earth Science imaging, spectral imaging, and sounding applications have always been among the most challenging in infrared photodetector technology due to the rigorous material growth, device design and fabrication demands. Future small satellite missions will present even more challenges for LWIR FPAs, as operating temperature must be increased so that cooler (and radiator) volume, mass, and power can be reduced. To address this critical need, we are working on following three technologies. 1) Type-II superlattice (T2SL) barrier infrared detector (BIRD), which combines the high operability, spatial uniformity, temporal stability, scalability, producibility, and affordability advantages of the quantum well infrared photodetector (QWIP) FPA with the better quantum efficiency and dark current characteristics. A mid-wavelength infrared (MWIR) T2SL BIRD FPA is a key demonstration technology in the (6U) CubeSat Infrared Atmospheric Sounder (CIRAS) funded under the ESTO InVEST Program. A LWIR T2SL BIRD FPA is also being developed under the ESTO SLI-T Program for future thermal infrared (TIR) land imaging needs. 2) The resonator pixel technology, which uses nanophotonics light trapping techniques to achieve strong absorption in a small detector absorber volume, thereby enabling enhanced QE and/or reduced dark current. 3) High dynamic range 3D Readout IC (3D-ROIC), which integrates a digital reset counter with a conventional analog ROIC to provide a much higher effective well capacity than previously achievable. The resulting longer integration times are especially beneficial for high flux/dark current LWIR applications as they can improve signal-to-noise ratio and/or increase the operating temperature. By combining the aforementioned technologies, this project seeks to demonstrate a cost-effective, high-performance LWIR FPA technology with significantly higher operating temperature and sensitivity than previously attainable, and with the flexibility to meet a variety of Earth Science TIR measurement needs, particularly the special requirements of small satellite missions.

Keywords: type-II superlattice, infrared detector, quantum efficiency, digital, focal plane array

1. INTRODUCTION

In this presentation, we will report our recent efforts in achieving high performance in Antimonides type-II strained-layer superlattice (T2SLS) based infrared photodetectors using the barrier infrared detector (BIRD) device architecture. The recent emergence of barrier infrared detectors such as the nBn [1] and the XBn [2] have resulted in mid-wave infrared (MWIR) and long-wave infrared (LWIR) detectors with substantially higher operating temperatures than previously available in III-V semiconductor based MWIR and LWIR detectors. The initial nBn devices used either InAs absorber grown on InAs substrate, or lattice-matched InAsSb alloy grown on GaSb substrate, with cutoff wavelengths of $\sim 3.2 \mu\text{m}$ and $\sim 4 \mu\text{m}$, respectively. While these detectors could operate at much higher temperatures than existing MWIR detectors based on InSb, their spectral responses do not cover the full (3 – 5.5 μm) MWIR atmospheric transmission window. There also have been nBn detectors based on the InAs/GaSb type-II superlattice absorber [3].

2. BARRIER INFRARED DETECTORS

Much has been discussed in the literature about the nBn and related devices, including XBn barrier photodetector [4-5], and unipolar barrier photodiode [5], since the publication of the influential paper entitled “nBn detector, an infrared detector with reduced dark current and higher operating temperature” by Maimon and Wicks in 2006 [1]. Common to this family of devices is the unipolar barrier. The term “unipolar barrier” was used recently to describe a barrier that can block one carrier type (electron or hole) but allows the unimpeded flow of the other [1, 4-5]. The concept of the unipolar barrier has been around long before they are called as such. The double-heterostructure (DH) laser, which makes use of a pair of complementary unipolar barriers, was first described in 1963 [6], soon after the birth of the concept of heterostructure devices.

The ideal nBn structure would have two n-type region (n) separated by a larger bandgap, undoped barrier layer (B), where the n-B heterojunctions have a larger conduction band offsets and zero valence band offsets. Such a barrier would block majority carrier electrons, but pass photogenerated holes. The nBn infrared detector is designed to reduce dark current (noise) without impeding photocurrent (signal). Central to the nBn operation is the strong suppression of generation-recombination (G-R) dark current due to Shockley-Read-Hall (SRH) processes. The nBn infrared detector is designed to reducing dark current (noise) without impeding photocurrent (signal).

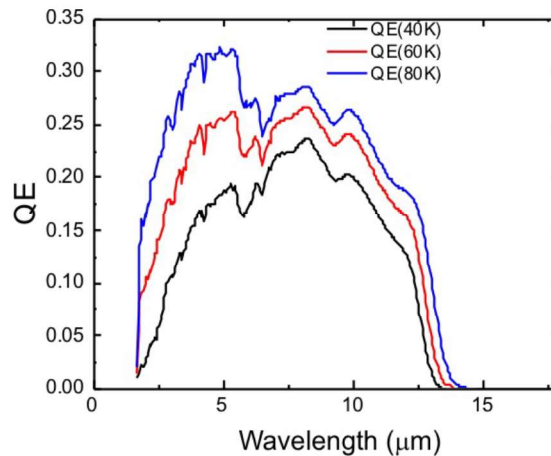


Figure 1. Backside illuminated spectral quantum efficiency (QE) for an LWIR detector measured at temperatures ranging from 40K to 80K.

Another important aspect of nBn and related structures is their effectiveness in reducing surface leakage current. The top surface of the active narrow gap absorber in the nBn detector is covered by the wide band gap barrier layer, and therefore does not need additional passivation to suppress surface leakage [1]. In a focal plane array (FPA) configuration, the array of top contacts could be defined by etching through the top contact layer but not the barrier layer [1]. In this configuration, the narrow gap absorber is not exposed, and therefore does not contribute to surface leakage. Finally, even in a deep-etched mesa configuration, where the side walls of the narrow gap absorber are fully exposed, the barrier can still block electron surface leakage effectively [1, 5]. An important aspect of the nBn detector (and unipolar barrier detector architecture in general) is the ability to block majority carriers without impeding the flow of minority carriers.

The InAs/InAsSb (Gallium-free) T2SLS has emerged as an alternative adjustable bandgap, broad-band III-V IR detector material to the more established InAs/GaSb type-II superlattice (T2SL). Recently, there has been growing interest in this material as an infrared detector absorber due to longer MWIR and LWIR minority carrier lifetimes in InAs/InAsSb strained-layer superlattice (SLS) than in InAs/GaSb superlattice (SL) and demonstrated an InAs/InAsSb SLS LWIR photodetector based on the nBn device design [7]. The T2SLS material can be grown on InAs or GaSb substrates, GaSb is available in 2", 3", 4" and 6" diameters formats.

3. LWIR BIRD FOCAL PLANE ARRAY

An InAs/InAsSb SLS nBn structure was grown on a 4-inch diameter low Te-doped GaSb (100) substrate in a Veeco Applied-Epi Gen III molecular beam epitaxy chamber equipped with valved cracking sources for the group V Sb₂ and As₂ fluxes. The nBn architecture is used for G-R and surface-leakage dark current suppression. Square mesa photodiodes of area 250 μ m x 250 μ m were fabricated along with detector arrays for responsivity and dark current measurements. The devices were not passivated nor treated with anti-reflection coating. Figure 1 shows the spectral quantum efficiency (QE) derived from back-side illuminated (through the GaSb substrate) spectral responsivity measured at temperatures ranging from 40K to 80K; the QE has not been corrected for substrate reflection or transmission. Accordingly, the spectral QE for 40K and 80K was taken at -50mV. The cutoff, taken at the wavelength at which the QE is 50% of that at $\lambda=12.5\mu$ m.

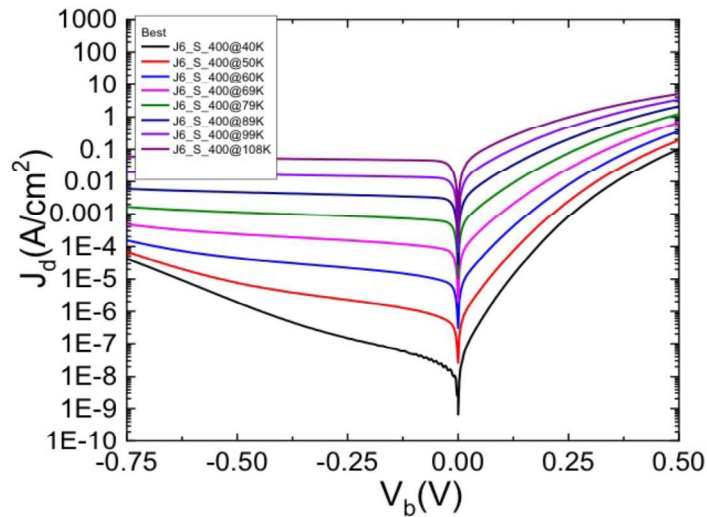


Figure 2. Dark current density (J_d) as a function of applied bias, measured at temperatures ranging from 40K to 108K.

Figure 2 shows the measured dark current density as a function of applied bias for temperatures ranging from 40K to 108K. The -50mV dark current density at 60K is $2.6 \times 10^{-5} \text{ A/cm}^2$. The presence of G-R dark current is apparent from the shapes of the J-V curves in Fig. 2 at temperatures below 60K; tunneling current can also be seen at lower temperatures and high reverse bias.

The detector material was used to fabricate $24\mu\text{m}$ pitch, 640×512 format arrays and hybridized to the SBF-193 readout integrated circuit (ROIC). The detector mesas are etched to just below the barrier; the pixels are not fully reticulated.

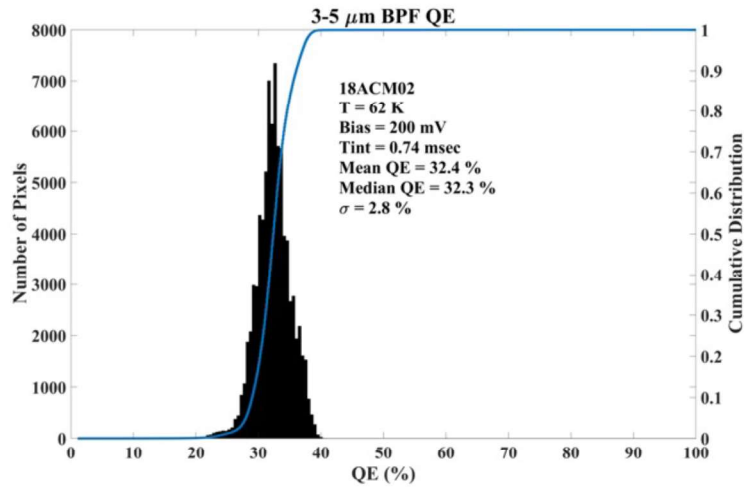


Figure 3. 3-5 μm broad-bandpass filter QE of the LWIR BIRD focal plane array (FPA) at 62K.

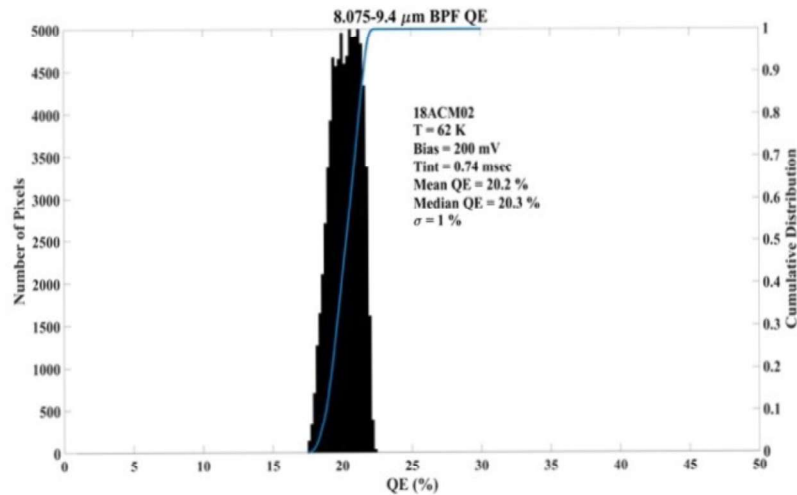


Figure 4. 8-9.4 μm broad-bandpass filter QE of the LWIR BIRD focal plane array (FPA) at 62K.

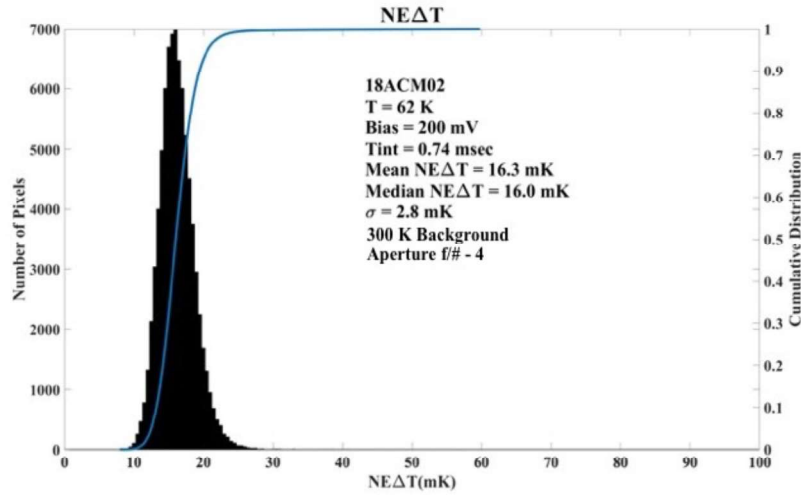


Figure 5. Noise equivalent temperature difference (NEΔT) of the 12.5μm cutoff BIRD FPA at 62K.

The noise equivalent temperature difference (NEΔT) provides the thermal sensitivity of an infrared imaging system and it is a very useful diagnostic tool to evaluate the full operational performance available. It is defined as the minimum temperature difference required at the target to produce unity signal-to-noise-ratio. Sequence of consecutive frames is collected for equivalent noise determination as well as other optical properties of FPA. The photo response matrices of FPA is derived at the low and high blackbody temperatures (i.e., 295 K and 305 K), and temporal noise matrix of FPA is estimated at the mid-point temperature by taking 64 frames of data. The temporal NEΔT of pixels are numerically evaluated from the relations, $NE\Delta T = \sigma_{\text{Temporal}} \Delta T / [\text{Mean}(T_H) - \text{Mean}(T_L)]$. The mean signal $\text{Mean}(T_L)$ and $\text{Mean}(T_H)$ are evaluated at blackbody temperatures of $T_L = 295$ K and $T_H = 305$ K. The temporal noise is measured at 300K using 64 frames, and $\Delta T \sim 10$ K.

The experimentally measured NEΔT histograms distributions of 640x512 pixels LWIR BIRD FPA at 62K operating temperature with blackbody temperature of 300 K and f/4 cold stop is shown in the Fig. 5. The experimentally measured NEΔT of 16.3mK is in fair agreement with the estimated NEΔT value based on the results of a single element test detector data.



Figure 6. An image taken with the 640x215 pixels LWIR Ga-free T2SLS FPA. Array operated at 62K with NEΔT of 16.3mK with f/4 optics at 300K background.

4. DIGITAL READ OUT INTEGRATED CIRCUIT

Infrared FPAs generally use non-silicon detector arrays to convert the infrared signal into an electrical signal. These detector arrays are hybridized via indium bump bonding process to a read out integrated circuit (ROIC). Conventional ROICs are based on analog electronic circuits. The modern ROICs are digital ROICs (DROICs). Conventional analog ROICs store charges at individual ROIC pixels and route them out via output taps to off-chip analog-to-digital converters (ADCs) or route them to on-chip column parallel ADCs. This method requires a very large ROIC in-pixel well depth to achieve high signal-to-noise-ratio (SNR). In DROICs the charges get digitized at ROIC individual pixel level with a counter by incrementing each time a small charge bucket gets filled. Ideally, this could provide a very high effective well depth for DROIC pixels compared to conventional analog ROIC pixels. Total well depth of DROIC pixel is given by the size of the charge bucket times the number of counts of the in-pixel counter [8-9].

The ultimate sensitivity (i.e., highest SNR) of an infrared FPA is determined by the maximum well depth of the ROIC pixels assuming the total noise of the FPA is determined by the shot noise (i.e., statistical fluctuations of the signal) of the photocurrent. Therefore, to achieve the maximum SNR,

$$SNR_{Max} = \frac{Signal_{Max}}{Noise} = \sqrt{Well\ Depth_{Max}}$$

Where, $Signal_{Max}$ is the maximum signal and noise is Poisson process limited statistical variation associated with the photocurrent. Thus, a maximum well depth of 25 million electrons yields SNR of 5,000 and well depth of 100 million electrons yields SNR of 10,000. Therefore, a DROIC with higher bit counter could provide a higher SNR or could operate a DFPA at higher operating temperature with same SNR as a conventional FPA (i.e., same detector array with an analog ROIC).

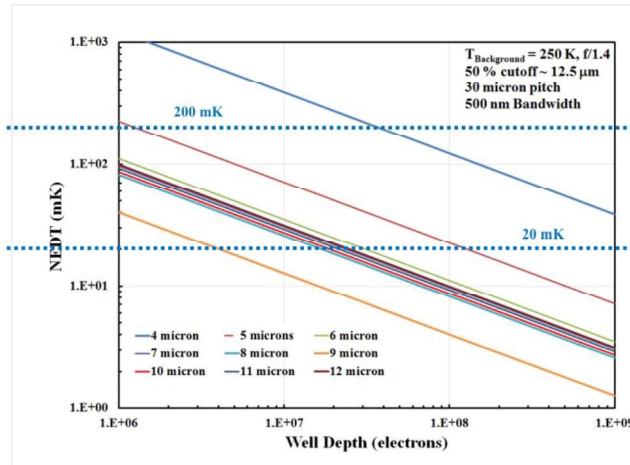


Figure 7. NEAT vs. ROIC well depth as a function of wavelength (from 4-12 μ m) for the 12.5 μ m cutoff LWIR BIRD FPA operating at 65K with 250K background and f/1.4 aperture. Dotted horizontal lines represent the 20mK and 200mK NEAT.

Figure 7 shows a case study performed with the experimental values obtained from the 12.5 μ m cutoff LWIR BIRD FPA operating at 65K with 250K background and f/1.4 aperture. We assumed 0.5 μ m bandpass for each wavelength (i.e., similar to TIRS instrument on Landsat 8). Figure 7 clearly shows that LWIR BIRD FPA operating at 65K can easily achieve 20mK NEAT with a DROIC with well capacity of 25 million

electrons for all wavelengths from 6-12 μ m. As shown in Fig. 7, same FPA could also achieve 20mK NE Δ T performance from 5-12 μ m if DROIC could provide 100 million electrons well depth. These kind of well depths (or even higher) are nominal to all DROICs.

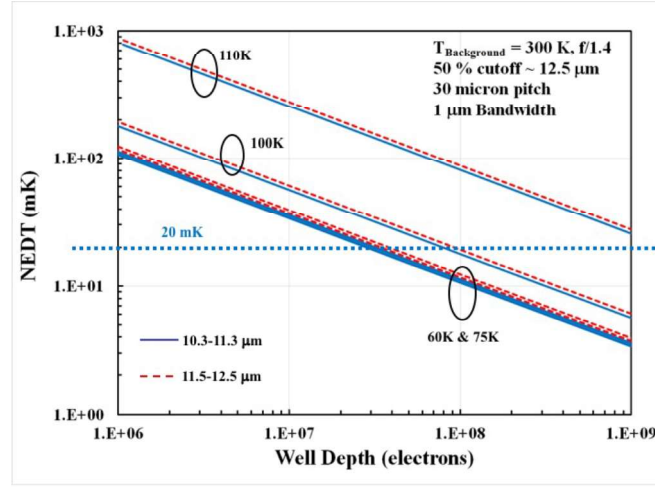


Figure 8. NE Δ T vs. ROIC well depth as a function of LWIR BIRD FPA operating temperature for two Landsat wavelength bands (from 10.3-11.3 μ m and 11.5-12.5 μ m) with 250K background and f/1.4 aperture.

Figure 8 shows a case study performed with the experimental values obtained from the 12.5 μ m cutoff LWIR BIRD FPA operating at various temperatures from 60K to 110K with 250K background and f/1.4 aperture. Fig. 8 clearly shows the two LWIR Landsat bands, from 10.3-11.3 μ m and 11.5-12.5 μ m can achieve 20mK NE Δ T with a DROIC with 100 million electrons well depth. Furthermore, LWIR BIRD FPAs could operate at even higher temperature with DROICs having greater effective well depths.

5. SUMMARY

Ga-free T2SLS LWIR BIRD FPA could easily operate at 20K higher operating temperature (HOT) (i.e. compared to QWIP FPA) due to the strong suppression of G-R dark current due to SRH processes as explained earlier. The light trapping resonator pixel concept offers a very effective solution to increase the QE of LWIR T2SL BIRDs. Another 20K higher operating temperature advantage can be achieved when we further improve the performance by hybridizing the T2SLS LWIR BIRD detector array to the high-dynamic range DROIC from DRS. Therefore, a T2SLS LWIR BIRD DFPA can easily operate at much higher operating temperature compared to a conventional LWIR FPA.

ACKNOWLEDGEMENT

The authors thank the NASA Earth Science Technology Office and Jason Hyon and Eastwood Im of Jet Propulsion Laboratory for encouragement and support. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. © 2019. All rights reserved. Government sponsorship acknowledged.

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